2D radiative gas dynamic model applied for Al plasma expansion under nanosecond pulsed laser action

- Laser plasma dynamics with radiation transfer taken into account

$$\frac{\partial \rho}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\rho u)+\frac{\partial}{\partial z}(\rho v)=0$$

$$\frac{\partial(\rho u)}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho u^2\right)+\frac{\partial}{\partial z}(\rho u v)=-\frac{\partial(p+\omega)}{\partial r}$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\rho u v)+\frac{\partial}{\partial z}\left(\rho v^2\right)=-\frac{\partial(p+\omega)}{\partial z}$$

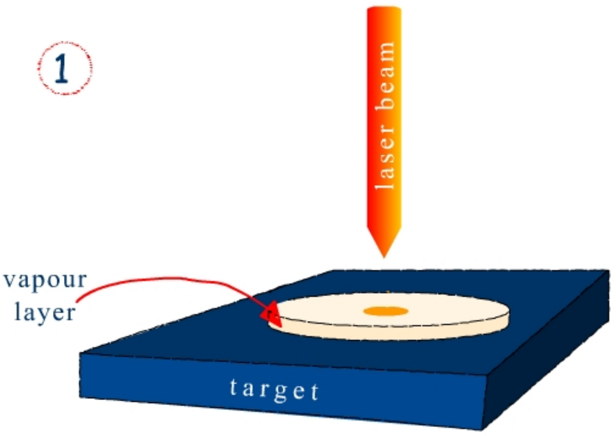
$$\frac{\partial(\rho e)}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\rho u e)+\frac{\partial}{\partial z}(\rho v e)=-p\left[\frac{1}{r}\frac{\partial(ru)}{\partial r}+\frac{\partial v}{\partial z}\right]-\left[\frac{1}{r}\frac{\partial q_r}{\partial r}+\frac{\partial q_z}{\partial z}\right]+\left[\frac{\partial G}{\partial z}\right]$$

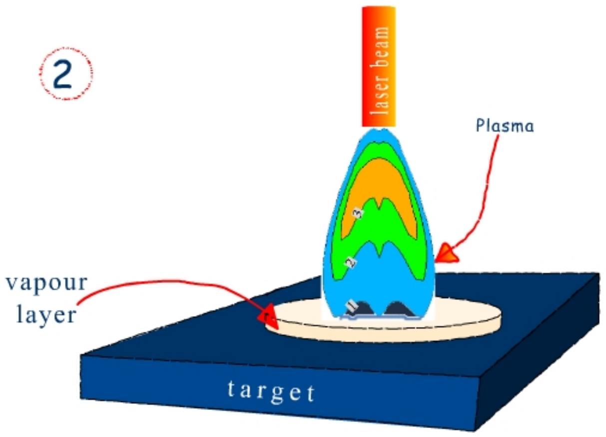
$$\vec{\Omega}\,\mathrm{grad}\, I_\nu+\kappa_\nu I_\nu=\kappa_\nu I_{b\nu} \qquad \vec{q}=\int_0^\infty \partial\nu\int_{-1}^{1} I_\nu \mu\,\partial\mu \qquad \frac{\partial G}{\partial z}-\kappa G=0$$

$$p=p(\rho,T),\quad e=e(\rho,T) \qquad 0<(r\times z)<\left(L_r\times L_z\right),\quad 0<t<t_{\max}$$

Here : ω denotes the artificial viscosity; q_r, q_Z are the components of the total radiative heat flux, G denotes the laser radiation intensity; is the unit vector of direction of the photon; I_ν, $I_{b\nu}$ are the spectral intensity of the radiation and the blackbody radiation; κ_ν, κ denote the absorption coefficients for the thermal radiation and the laser radiation, respectively

- Simulation Schema: Initial Conditions





- Plasma expansion

Computational parameters and initial conditions

Laser pulse intensity $G_0=10^9$ - 2×10^{10} W/cm^2, pulse duration τ = 10 ns, spot diameter D = 0.5 mm. laser wavelength λ = 1.06, 0.532, 0.248 μm. The laser pulse intensity is considered to be uniformly distributed in space and time, i.e. $G \equiv G_0$. The chosen parameters correspond to the fluence of 10 - 200 J/cm^2 and the pulse energy of 0.02 -0.4J. The initial parameters of the plasma layer $0 \le (r \times z) \le (r_{hot} \times z_{hot})$, $T(0, r, z) = T_{hot}$, $\rho(0, r, z) = \rho_{hot}$ are chosen as follows : $z_{hot} = 20$ µm, $T_{hot} = 0.5$ eV, $\rho_{hot} = 5 \times 10^{-2}$ cm^{-3}, $r_{hot} = R$. The sizes L_r, L_z of the computational domain are $L_r = 5$ cm , $L_z = 25$ cm, the background temperature and the density are $T_0 = 0.03$ eV , $\rho_0 = 3 \times 10^{-6}$ g/cm^{-3} respectively, which corresponds to the background pressure of 3×10^{-2} bar.

- ## Plasma Radiative Properties

The absorption coefficients κ_ν, κ are determined by the Hartree-Fock-Slater quantum-mechanical model. The total absorption coefficient is written as,

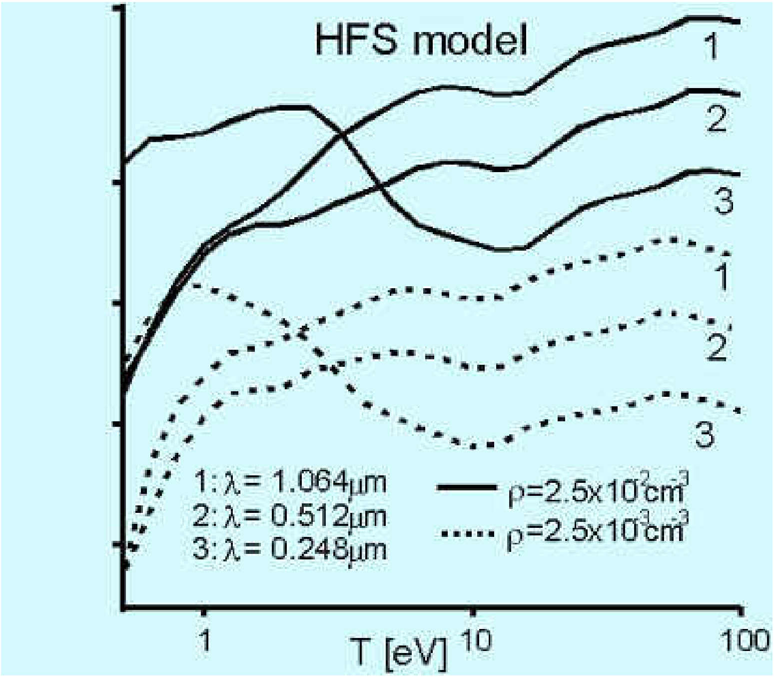
$$\kappa_\nu = \sum_i n_i \sigma_i^{bf}(\nu) + \sum_{jk} n_j \sigma_{jk}^{bb}(\nu) + \kappa_\nu^{ff}$$

where n_i, n_j denote the population of the excited states of atoms and ions, κ_ν^{ff} is the Inverse Bremsstrahlung absorption coefficient, σ_i^{bf}, σ_{jk}^{bb} are the absorption cross-sections for the bond-free and bond-bond transitions. Summation is performed for all the permitted transitions included into the model. The cross-section for the bond-bond transition is determined as the product of the oscillator strength and the spectral function of the line, the latter being calculated with account for several line broadening mechanisms.

The multi-group diffusion approximation is applied to describe the radiation transfer : κ_ν is assumed to be independent on frequency within the specified spectral sub-intervals (groups), and is substituted by the Planck mean absorption coefficient:

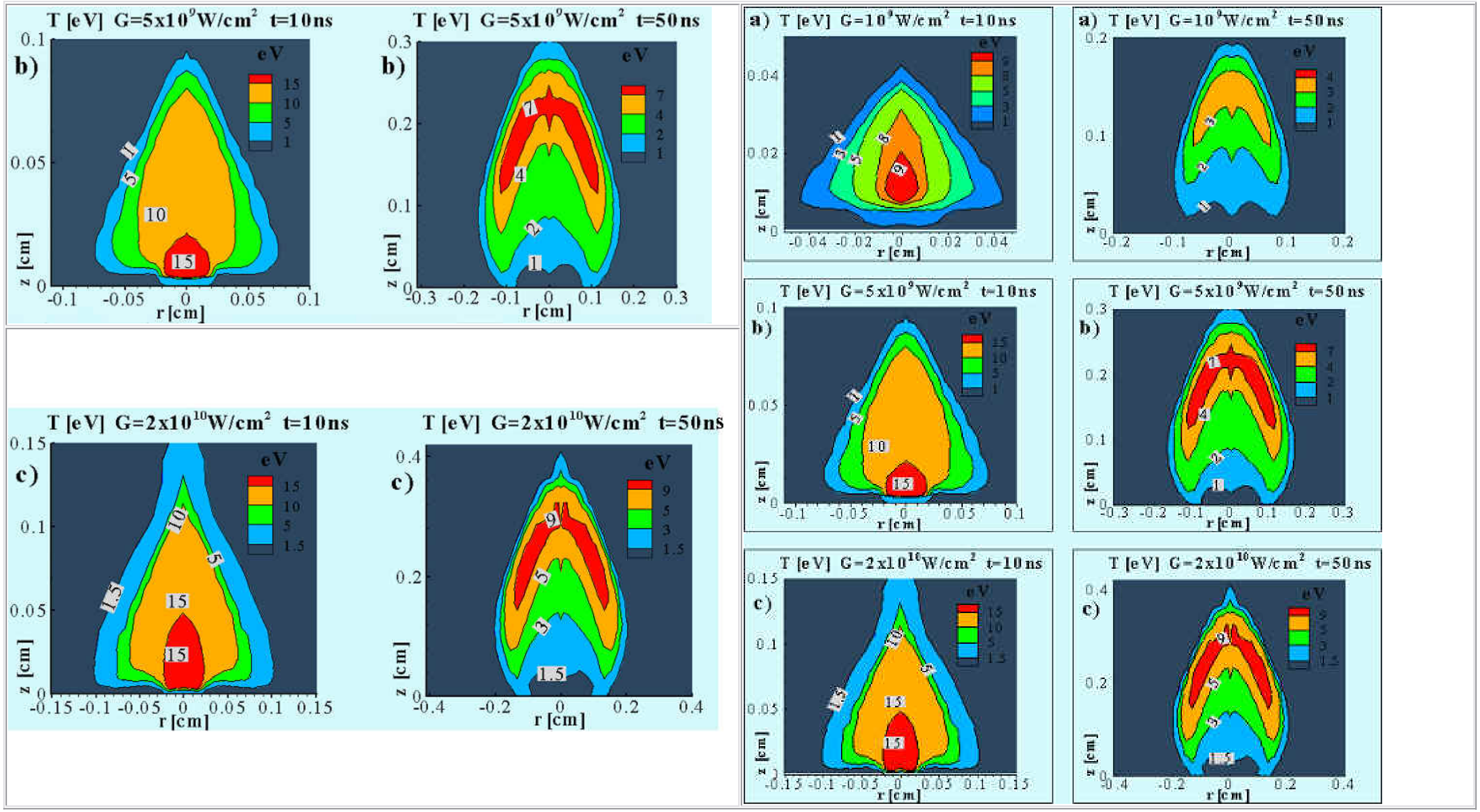
$$\kappa_{\Delta\nu} = \int_{\Delta\nu} \kappa_\nu U_{b\nu} \, d\nu \Big/ \int_{\Delta\nu} U_{b\nu} \, d\nu$$

$U_{b\nu}$ means the energy density of blackbody radiation

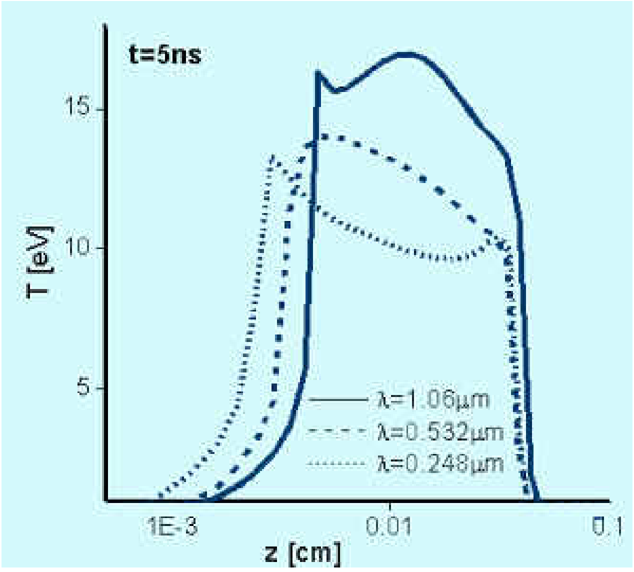
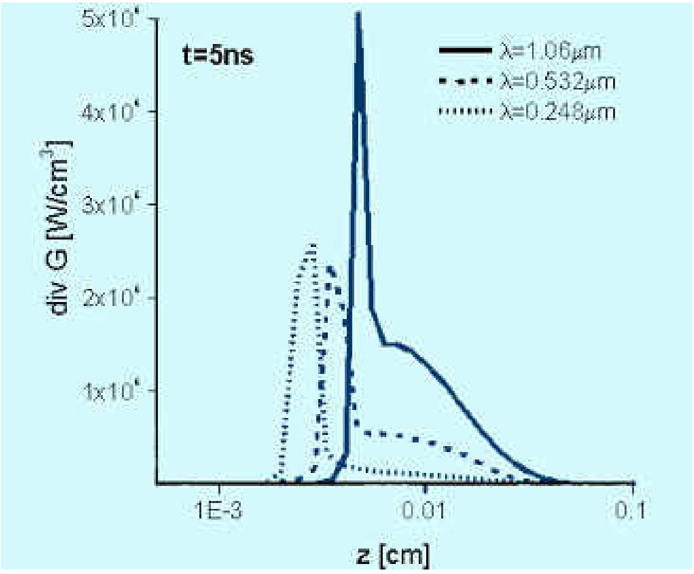


Temperature dependence of the absorption coefficients *k* of the laser radiation for several laser wavelengths.

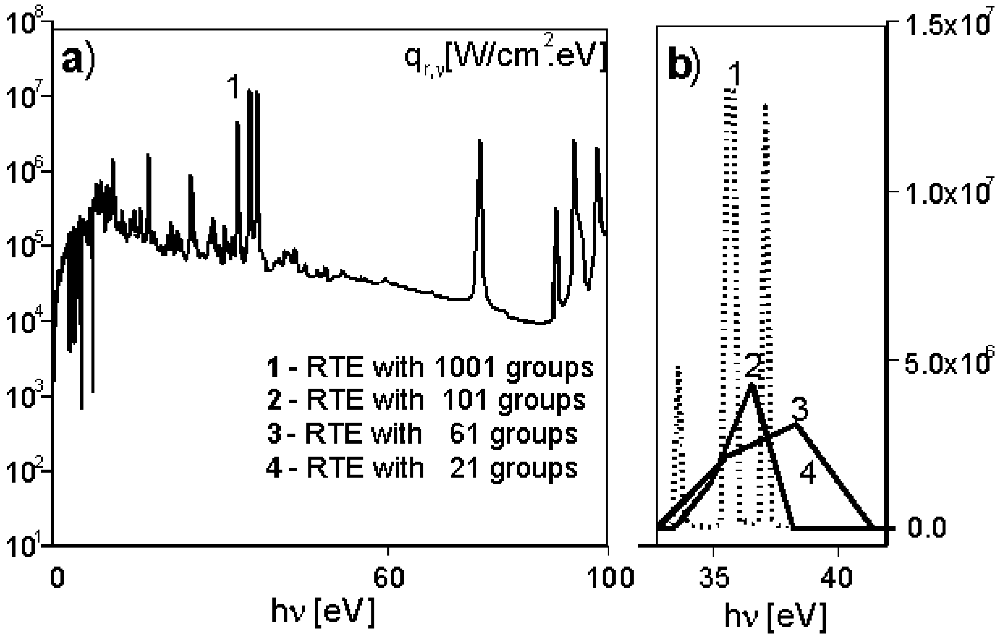
- Plasma expansion



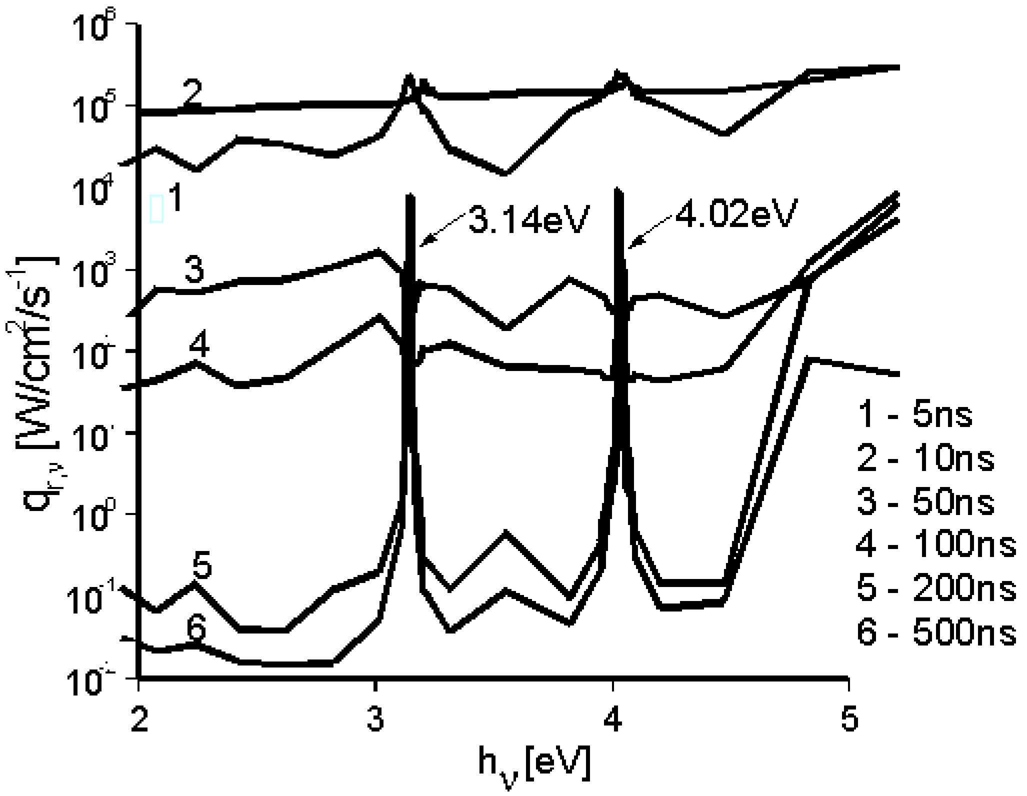
- Influence of laser wavelength

	
Plasma temperature profile along the beam axis for $G_0 = 5 \times 10^9$ W/cm^2, $t = 5$ns.	Laser energy release rate at the beam axis *div G(z,r=0)* for laser wavelength λ = 1.06, 0.532, 0.248 μm, *t*=5ns.

- Plasma Spectrum Simulation



Spectral radiative heat flux at the side boundary at t = 10ns for laser intensity $G_0 = 5 \times 10^9$ W/cm^2



Evolution of spectral lines Al I (3.14 eV) and Al I (4.02e V) of radiative heat flux at side boundary for laser intensity $G_0 = 5\times10^9$ W/cm^2. These lines correspond to the transition from the first $4^2S_{1/2}$ and second $3^2D_{3/2,5/2}$ excited levels of neutral Al atom to the ground state.

Conclusion

Radiative transfer affects the expansion of laser plasma in the intensity range 10^9 - 2X10^{10} W/cm^2 :

1. The radiative energy losses can reach 60 % of the laser pulse energy absorbed by the plasma and lead to a proportional decrease of the temperature;

2. The spectral composition of the escaping radiation is non-equilibrium and qualitatively corresponds to the optically thin approximation;

3. By using the detailed frequency grid for the selected spectral intervals the model makes it possible to observe evolution of the spectral lines.